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LIMITED EVALUATION OF AN 802.11b AIR-TO-AIR WIRELESS DATA LINK (PROJECT HAVE HALO II)

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FINAL TECHNICAL INFORMATION MEMORANDUM

Approved for public release; distribution is unlimited.

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EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIAL COMMAND
UNITED STATES AIR FORCE

This Technical Information Memorandum (AFFTC-TIM-07-01, Limited Evaluation of an 802.11b Wireless Data Link, Project Have HALO II) was prepared and submitted under Job Order Number M07C0100 by the Have HALO II test team, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

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PREFACE

The Have HALO II Test Team would like to thank Mr. Chris Howell for his generous support of this test project. The training provided by Chris enabled the test team to use the equipment and data collection devices. Chris also coordinated for the use of critical equipment for all flight test sorties. Chris's support during the planning, training, and ground testing efforts ensured the successful completion of this test project.

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EXECUTIVE SUMMARY

This final technical information memorandum presents the test procedures and results for the Have HALO (Huron Airborne Link Optimization) II Test Management Project (TMP). The Have HALO II Test Team performed flight tests to determine the range and bandwidth capability of an 802.11b air-to-air Wireless Fidelity (WiFi) data link, and to identify the data link's performance characteristics. The Commandant of USAF Test Pilot School (TPS) directed this program at the request of Headquarters, Air Combat Command (HQ/ACC/A8G). All testing was accomplished under TPS Job Order Number M07C0100. Using two modified C-12C aircraft a total of 35 hours of flight test were flown during 14 test sorties in Edwards Restricted airspace and Palmdale/Lancaster, CA airspace during March 2007 to accomplish the test objectives.

The Have HALO II Test Team used two modified C-12C Huron twin engine turboprop aircraft, serial numbers 73-01215 and 76-00158 as test aircraft. Both test aircraft were modified with S-Band antennas mounted on the top and bottom of the fuselage to transmit and receive the WiFi signals. The system under test (SUT) onboard each aircraft consisted of a radio frequency (RF) signal amplifier for each antenna, Harris Corporation's wireless access point, Harris Corporation's SecNet11® wireless network card, and one laptop with a Microsoft® Windows® XP operating system.

The test team successfully completed a limited evaluation of an 802.11b air-to-air WiFi data link between two C-12C test aircraft. The test team determined the maximum range capability for 1 megabit per second (Mbps) and 11 Mbps transmissions over the WiFi data link when transmitting at 1 or 5 Watts of amplifier power, corresponding to 0.32 and 1.58 Watts of effective isotropic radiated power, respectively. Diagnostic and performance statistic software on the laptops were used to gather the data rate and performance statistics in flight, while post flight analysis was conducted to retrieve the data link range statistics. The flight test results closely matched the predicted maximum ranges found using an RF link prediction model, accounting for cabling losses, amplification, antenna gain, free space losses, amplifier receive gain, and the published SecNet11® receiver sensitivity. Increased reception range could have been achieved using lower loss RF cabling and placing the amplifier closer the antenna. Of the available configurations tested (ad hoc, infrastructure and bridge), ad hoc was found the most reliable. The test team also demonstrated the capability of transmitting and receiving text files, still images, pre-recorded video, and streaming, live webcam video between the two test aircraft.

Overall, several recommendations to continue testing were made to improve the statistical results of the test and to further quantify how in-band RF noise affects the reception range of the data link. The next logical steps are to reduce the cabling losses in the present configuration, increase the level of amplification, and begin testing at a variety of altitudes. These actions will expand the testing envelope and help evaluate the in-band RF effects – ultimately leading to the determination of the data link's ability to handle current and next generation operational applications.

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INTRODUCTION

Background

Air Combat Command contracted Lockheed Martin Aerospace Company to investigate COTS wireless network applications. Lockheed Martin requested Test Pilot School (TPS) to conduct testing in support of this investigation. This testing was planned for three consecutive test projects, of which this test was the second. The previous Have HALO test project (Have HALO I) completed testing for an 802.11b air-to-ground Wireless Fidelity (WiFi) data link using a single airborne C-12 and a ground station (Ref 1, 2). The test objectives included determining the reception envelope and performance characteristics for the air-to-ground data link.

The Have HALO II test project determined the reception envelope and performance characteristics of Harris Corporation's SecNet11® demonstration card WiFi data link. The testing provided data to determine the ability of the data link to handle current and next generation operational applications. The applications were expected to require robust, high speed links to transmit real-time tactical information, enabling time and space task management for coordinating warfare and information sharing.

The Have HALO II testing was conducted in three phases. Phase 1 evaluated the WiFi data link between two mobile ground stations. Phase 2 involved ground testing with the data link equipment installed on the aircraft to ensure functionality before flight testing. Phase 3 involved flight testing to evaluate the objectives and measures of performance.

Program Chronology

The test team received the program information document (PID) on 30 October 2006. Modification of the aircraft began on 21 Feb 2007 and was completed on 9 Mar 2007. 35 hours of flight testing were conducted 14-29 Mar 2007. A total of seven formation test flights (14 sorties) were flown, as shown in table 1. A detailed summary of the test points flown is presented in appendix D.

Table 1. Summary of Test Flights

Flight	Description
1	Infrastructure Mode Envelope Definition
2	Bridge Mode Envelope Definition
3	Ad Hoc Mode Envelope Definition
4	Ad Hoc Mode Envelope Definition
5	Ad Hoc Mode Envelope Definition
6	Ad Hoc Mode Performance and High Noise Effects
7	Infrastructure / Ad Hoc Mode Performance and High Noise Effects

Test Item Description

The system under test (SUT) consisted of airborne antennas with amplifiers, Harris Corporation's wireless access point and SecNet11® demonstration wireless card, Dell Latitude® PCs with Windows® XP and XP Performance Monitor software, two web-based cameras for real-time video transfer, and two GARMIN® GPS units for data link synchronization. One Itronix Duo-Touch® tablet PC in each aircraft monitored the wireless data link network performance and ambient noise in the WiFi spectrum. The airborne data link was transmitted over the omnidirectional antennas at a frequency of 2.4 GHz to 2.5 GHz. Either 1 or 5 Watts (W) of amplification was used, which produced 0.32 or 1.58 W of effective isotropic radiated power. The SUT airborne GPS receiver was connected to a GPS antenna mounted on the tail of the C-12. NetStumbler® software was used to gather signal-to-noise ratio (SNR) data. GPS position was displayed on a moving-map display using FalconView®. Microsoft® NetMeeting® software was used to conduct text and video chat over the data link. Table A-1 lists the components that were used during testing. A more detailed test item description can be found in appendix A.

Test Objectives

The overall test objective was to determine the data link reception envelope and the performance of an airborne 802.11b WiFi data link as a function of range, elevation, and azimuth about an aircraft configured for WiFi communications. The specific test objectives were:

- Determine the Air-to-Air Data Link Reception Envelope

- Determine the Data Link Performance Characteristics

All test objectives were met.

TEST AND EVALUATION

General

The overall test objective was to determine the data link reception envelope and the performance characteristics of an air-to-air 802.11b WiFi data link. The utility of an air-to-air data link could be understood in three terms: range, data rate, and efficiency. Efficiency was expressed in terms of error rates because they reflect inefficient use of data rate through retransmission of data. All flight test efforts were directed at determining those terms. The three physical configurations of the air-to-air data link were: Infrastructure, Bridge, and Ad Hoc. Each configuration is described in appendix A. Within each of the physical configurations, data rates and the level of amplification were selectable. This cast the physical configurations into the following testable configurations: Infrastructure (automatic (AUTO), 11 megabits per second (Mbps), 5.5 Mbps, 2 Mbps, 1 Mbps; 1 W, 5 W), Bridge (11 Mbps, 5.5 Mbps, 2 Mbps, 1 Mbps; 1 W, 5 W), and Ad Hoc (AUTO, 11 Mbps, 5.5 Mbps, 2 Mbps, 1 Mbps; 1 W, 5 W). The primary physical configuration tested was Ad Hoc, under the following data rate and amplification conditions: 11 Mbps (1 W, 5 W), and 1 Mbps (1 W, 5 W). For all 1 W and 5 W amplifier power settings, the effective isotropic radiated power was 0.32 and 1.58 W respectively.

Design of experiments (DOE) analysis was conducted on the test configurations to orthogonalize and reduce the size of the test matrix. Statistical analysis was performed on the flight test data to determine the 95 percent confidence interval (CI) for the reception envelope in azimuth and elevation about the aircraft; determine the effects of the method of test used; determine the impact of data rate selection; and determine the impact of in-band radio frequency (RF) noise.

Air-to-Air Data Link Reception Envelope

The first test objective was to determine the air-to-air data link reception envelope between the two C-12C aircraft, while testing all three physical configurations of the data link–Infrastructure, Bridge, and Ad Hoc. Although each data link configuration was different, the flight test procedures in terms of pre-takeoff actions, flight test techniques used (varying range, varying elevation, constant relative position, and maneuvering flight), and data collection techniques remained the same. To define the data link reception envelope, a set of flight test techniques (FTTs) were designed to both capture azimuth and elevation dependencies, while also permitting a DOE analysis. Several user options of the data link were available, so the results attained are reported in an effects-based fashion to clarify all the data link configuration considerations.

Procedures

Data link duties were assigned to each aircraft based upon whether it was the *control* or the *host* aircraft. The host aircraft was responsible for changing data rates, changing amplifications, maintaining the link, and monitoring the GPS data collection. The control aircraft was responsible for actively conducting data file transfers or signal-to-noise ratio (SNR) measurements, in addition to the responsibilities listed for the host aircraft. Due to the flight test workload requirements of the control aircraft, two flight test engineers (FTEs) were scheduled, when possible, to fly on that aircraft (test conductor and laptop operator). A single FTE was scheduled to fly on the host aircraft.

For all flight tests, the air-to-air data link was configured on the ground prior to takeoff. Each physical configuration can be seen in appendix A. The following actions were completed before taxi: setting up the data link configuration; establishing over-the-air connectivity between C-12s; updating the laptop system clock with GPS time; configuring Windows® XP Performance Monitor to collect data rates and performance characteristics; starting NetStumbler; and setting altimeters to the local setting. Configuring the data link consisted of establishing physical connectivity to the amplifiers and setting the power level on the amplifiers (either 1 or 5 W). Over-the-air connectivity was verified through conducting a file transfer. Each laptop was updated with GPS time to synchronize the aircraft GPS position files with the performance statistics log files. The Windows® XP Performance Monitor file was configured to collect all network interface characteristics – data transfer rates and performance statistics. The sample rate was set to 1 Hertz – the fastest rate available. NetStumbler was configured from the control aircraft and was used to collect SNR data. The software could only be used during Infrastructure configuration testing due to architecture (physical configuration) requirements. The altimeters were set to local pressure to maintain a consistent test methodology.

Once all pre-flight actions were accomplished, an interval takeoff was conducted. A rejoin in extended trail was initiated following the takeoff. Data transfers were conducted throughout the climb to monitor the link performance and facilitate an efficient entry to the first test maneuver. All data transfers consisted of a data pull and a data push to maintain a steady, overall data transfer rate. All file transfers were initiated from the control aircraft – a data pull was a file transfer from the host aircraft to the control aircraft, while a data push was a file transfer from the control aircraft to the host aircraft. The overall data rate was higher when both a data push and a data pull were conducted at the same time. The full bandwidth available to the network was used ensured the data link was always data rate saturated.

The FTTs flown addressed one or more of the following areas: defining the reception envelope in 30 degree increments of azimuth (varying range, varying elevation, constant relative position FTTs); examining the effect of altitude separation (varying elevation FTT); gaining statistical significance without increasing the number of the runs (constant relative position FTT); examining antenna blanking events (maneuvering flight FTT); and/or examining high noise effects (Palmdale/Lancaster runs). Visual depictions of the FTTs flown for this flight test are found in appendix C. All outbound FTTs commenced with maximum available data rate and terminated 10 seconds after link break. All inbound FTTs started from a range greater than link break and required the laptop operator to initiate data transfers at the first indication of link availability.

Configuration Effects

All three physical data link configurations available for test were evaluated first during ground tests prior to flight test. Over 28 hours of ground tests suggested all three configurations would work under the conditions the data link would be exposed to during flight tests. However, only the Ad Hoc configuration was found robust (free of hardware/software resets) enough to continue flight testing. The Infrastructure configuration was the first physical configuration tested and was used to examine the best test method (data file transfers or SNR measurements) for determining the distance to link break – the point in which data file transfers could no longer be conducted. While the best test method was able to be isolated from the flight test dedicated to Infrastructure configuration testing, the configuration itself could not continue to be used due to the amount of time required to recover from the faults. The SecNet11® card used in the laptop of the control aircraft had to be reset over five times in flight. Each time this occurred, the flight test maneuver had to be repeated because the data link was rendered totally inoperable during those events.

The Bridge configuration was tested during the second flight test. The same card resets were required. The card in the host aircraft (configured as the "slave") required multiple resets, which disrupted the test. The faults were relayed back to Harris Corporation for further analysis and investigation. **Investigate why SecNet11® demo cards experienced frequent failures during flight test in Bridge and Infrastructure configurations. (R1)[1]**

The Ad Hoc configuration was tested during the third flight test. The same cards were used as during the Infrastructure and Bridge configurations. No faults were encountered during the third flight test or during any of the remaining four flight test sorties which performed Ad Hoc configuration testing. Due to the reliability of the Ad Hoc configuration, it was selected for the remainder of flight test efforts. During the first three flight tests, a relationship between the range reception and the selected data rate was discovered and is discussed in the data rate effects section.

Data Rate Effects

The first three flights demonstrated an increased data link reception range when a 1 Mbps data rate was selected rather than AUTO data rate. AUTO was predicted to automatically reduce the data rate from 11 Mbps to 5.5 Mbps to 2 Mbps and then down to 1 Mbps as the signal to noise ratio (SNR) deteriorated with increasing range. While AUTO did reduce the data rate as range increased, the data link reception envelope was smaller than when 1 Mbps was selected. Further testing was done to quantify the impact data rate selection had on the reception range. Two range values were determined for each maneuver flown. The *full data rate range* represents the range at which the data rate dropped below 90 percent of its highest value for at least five seconds. The other range measured was the *link break range* which is the range where the data link did not transfer any data for at least five seconds. Figure 1 illustrates the 95 percent confidence interval (CI) for link break ranges achieved with 1 Mbps, 11 Mbps and AUTO data rate selections. There was not a significant difference between the AUTO and 11 Mbps; however, the range reception nearly doubled when 1 Mbps was selected. **For maximum range, select 1 Mbps data rate. (R2)**

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[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

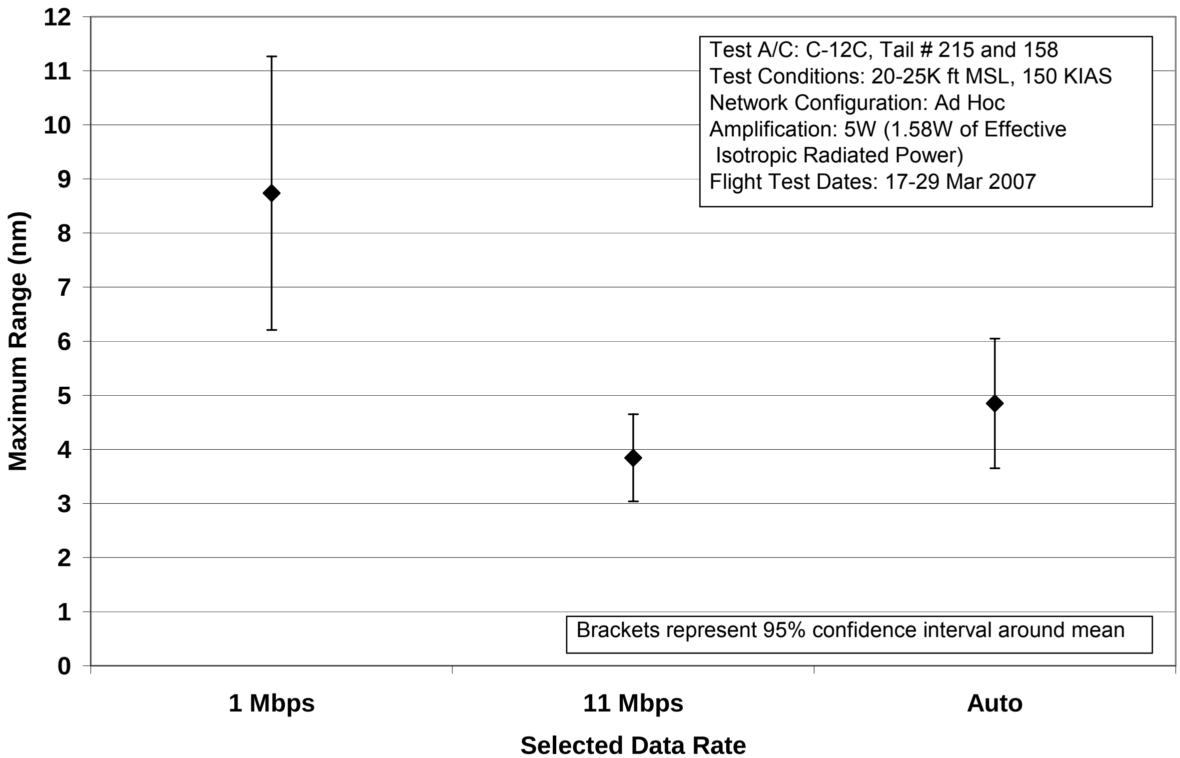

Figure 1. Reception Range Dependence on Selected Data Rate

Actual Data Rates

While the data rates selected were AUTO, 11 Mbps, 5.5 Mbps, 2 Mbps, and 1 Mbps, the actual over-the-air data rates were much lower. The actual data rates are identified in table 2. The data rates were a function of the physical configuration (Infrastructure, Bridge, or Ad Hoc). Since both Infrastructure and Bridge configurations used an access point, the data rates were the same and limited by that device. Knowing the over-the-air data rate gives the user baseline information for developing future applications. **Publish the actual data rates as a function of the physical configuration and data rate selection for future application considerations. (R3)**

Table 2. Actual Data Rates

Selected Data Rate	Actual Data Rates (Mbps)		
	Infrastructure	Bridge	Ad Hoc
AUTO	4.0	N/A	4.4
11 Mbps	4.0	3.6	4.4
5.5 Mbps	3.0	3.6	3.0
2 Mbps	1.4	3.6	1.4
1 Mbps	0.7	3.6	0.7

Power Effects

Amplification was selectable between 1 W and 5 W. Selectable amplifiers were used for the flight test, so the effects of high noise environments outside the Edwards Restricted Airspace could be observed. Transmit power for all 802.11b devices were limited by Federal Communications Commission (FCC) part 15.247 to 1 W or 30 dBm of transmitter power delivered to a 6 dB isotropic antenna, effectively 36 dBm of effective isotropic radiated power (Ref 1). Clearance to exceed the FCC criteria could be granted inside the Edwards Restricted Airspace by the Edwards AFB Spectrum Management Office; however, their jurisdiction was limited to Edwards Restricted Airspace. For this reason, 1 W amplification was used outside the restricted airspace for high noise testing and 5 W amplification was used inside the restricted airspace to quantify the effects amplification had on the reception range. Some additional 1 W testing was conducted in the Edwards Restricted Airspace to provide a baseline reception range for comparison with the high noise test points.

Measured Range

The factors available for testing were data link configuration, data rate, and power. The decision to test at 11 Mbps and 1 Mbps was made to examine the extremes of the data link's utility. The 11 Mbps data rate offered the greatest available data link utility in terms of throughput available for applications, while the 1 Mbps data rate offered the longest range available to the data link. The decision to conduct 1 W and 5 W testing was based on examining the impact of transmit power and high levels of RF noise on the data link reception range. Given those decisions, the Ad Hoc configuration was placed into the following testable configurations for DOE analysis: 11 Mbps/5 W, 1 Mbps/5 W, 11 Mbps/1 W, and 1 Mbps/1 W.

DOE analysis was conducted on the four available configurations to develop an orthogonal test matrix of varying range and varying elevation maneuvers. The analysis was focused on examining the azimuth and elevation dependence of the data link reception envelope. The full matrix of test points can be found in appendix D. A single run of each test point was planned; however, some maneuvers were conducted multiple times due to airspace availability and air traffic conflicts during maneuvers. Overall, the results of the entire set of maneuvers were statistically analyzed to determine the data link reception envelope and its dependence on azimuth and elevation.

A total of 28 test points were evaluated for the 5 W amplification test points. From the analysis, no azimuth or elevation dependencies yielded a statistical significance. Although the raw test results appeared to have an azimuth dependence, particularly during tail-to-tail maneuvers, there were not enough test runs to yield a statistical significance of this phenomenon. Free of azimuth and elevation dependencies, the range results from each maneuver were combined and analyzed as an amalgam to determine the 95 percent CI of the reception envelope for the 11 Mbps and 1 Mbps data rates. The 95 percent CI for 11 Mbps and 1 Mbps data rates under 1 W and 5 W amplification can be seen in figure 2. The 11 Mbps data rate region to link break of the reception envelope was between 3.0 to 4.7 nm between the aircraft, and the 1 Mbps data rate region to link break was between 6.2 to 11.3 nm. In general, the large intervals were primarily due to the instances in which the tail-to-tail test points yielded shorter ranges, while many of the 60 degree varying range and varying elevation test points yielded longer ranges. Flying more replicates of the test points will reduce the confidence intervals and provide a realistic azimuth and elevation dependence of the data link reception envelope. These dependencies are necessary to reveal the installed antenna effects, but more importantly they provide the operator with the best and worst locations of the reception envelope. **Fly additional varying range and varying elevation test points to refine the azimuth and elevation dependence of the data link reception envelope. (R4)**

The same analysis was conducted on the 18 flight test maneuvers used to collect and define the data link reception envelope under 1 W of amplification. No azimuth or elevation dependencies were present in the analysis. The 95 percent CIs for 1 Mbps and 11 Mbps data rates can be seen in figure 2. The 11 Mbps data rate region to link break of the data link reception envelope was between 0.76 to 2.3 nm between the aircraft and, the 1 Mbps data rate region to link break was between 2.4 to 4.6 nm.

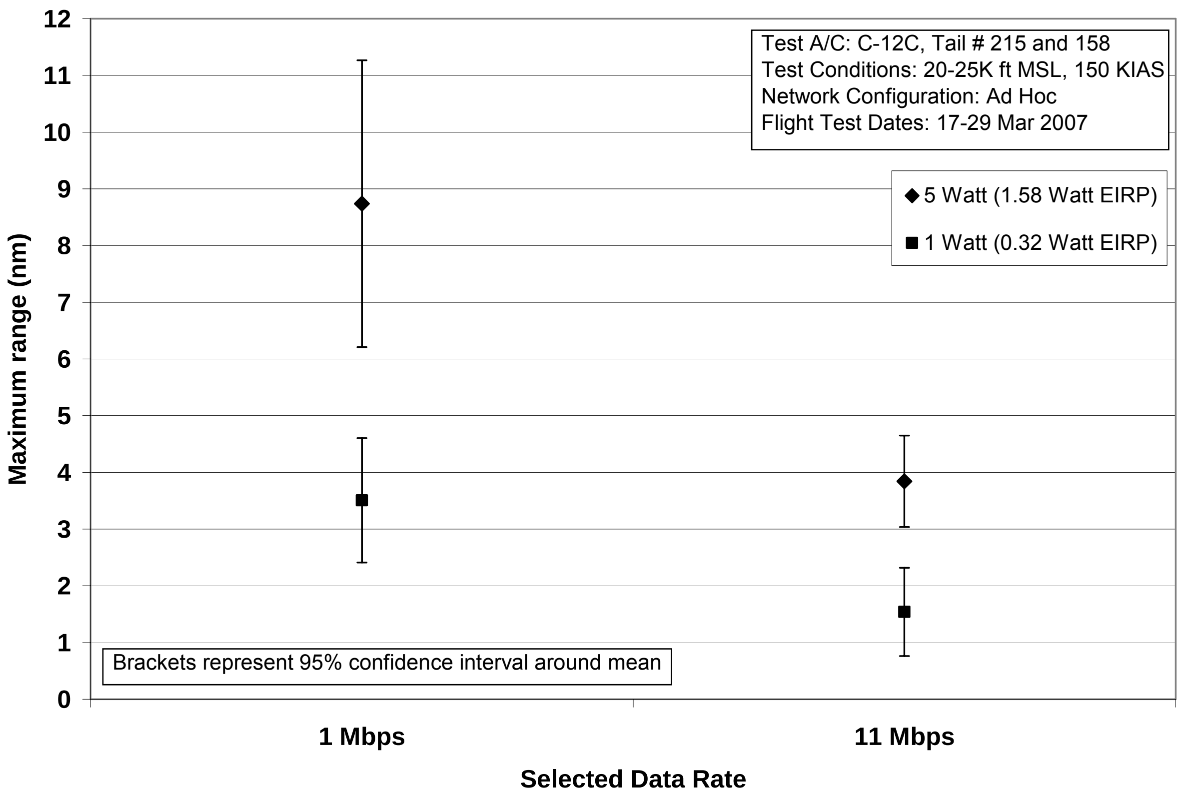

Figure 2. Data Link Reception Range

Losses and Noise Effects

One of the most important attributes of an operational tactical data link is range. Good range performance relaxes the operational bounds a pilot must regularly consider to maintain connectivity. The standard RF range equation was applicable to this test. In this equation, range was a function of amplification, antenna gain, cabling losses, and free-space losses. Based on test team operational experience, the maximum ranges for maximum data rate and for basic link maintenance were smaller than that desired for an operational data link. This was because of the SUT low effective radiated power, stemming from low amplification levels and high cable losses. The amplification levels were limited by FCC regulations concerning 802.11b applications. The tests were conducted with the maximum amplification levels allowed under those regulations. Cable losses were a function of cable type and cable length. Cabling accounted for a 20-dB loss, as shown in figure B-1 of appendix B. Each tested installation is described in detail in appendix A.

Amplified output power was fixed at either 1 W or 5 W (selectable). Approximately 16 dB of cabling losses were present between the transmitting amplifier and the receiving amplifier. After the fixed receiving amplifier gain, a further 4 dB of loss was present before connection to the computer. In total, this led to 20 dB of loss between the transmitting amplifier and the receiving computer. This signal reduction reduced the data link range from what could have been possible for this test. For future applications, cabling losses of this magnitude will greatly reduce range and decrease operational utility. An additional technique to minimize cable losses would be to put the amplifiers as near the antennas as possible. **Use low-loss cabling for the appropriate frequency and mount the amplifiers as near the antenna as possible to maximize data link range. (R5)**

The achievable data rate was a function of SNR. The previous discussion was concerned with the power of the signal. The noise level will also be important to future applications, but will be difficult to predict and even harder to control. Testing showed high sensitivity to noise, especially when operating near the maximum range. The test team did not predict significant effects due to noise when operating at the test altitude of 20-25,000 feet MSL because of the low power of home WiFi networks. In actuality, noise appeared to be a factor even at those altitudes due to other devices transmitting RF energy in the 802.11b frequency band. While those devices could not be identified, the Itronix Duo-Touch Tablet PCs carried in the test aircraft incorporated spectrum analysis tools which identified varying noise levels at altitude. Unfortunately, the spectrum analysis recording and playback functionality was limited, so noise level was gathered by the FTE in the aircraft only by visually watching the noise level and annotating when more than -60 dBm of noise was encountered. As a specific example, higher noise was observed in the vicinity of China Lake/Ridgecrest on flight #5 which caused the data link to drop while within approximately 3 nm lateral spacing of the developed area. Outside of that area of noise, the data link quality was good and high data rate was achieved.

To further quantify the effects of noise, several runs were made at low altitude (3,000-4,000 feet AGL) over the Lancaster/Palmdale urban area. These test points were conducted in the Ad Hoc configuration with 1 W amplification and 1 Mbps and 11 Mbps data rate selected. Using the constant relative position FTT, the maximum range for data link operation was 2,000 feet for 1 Mbps and 1,000 feet for 11 Mbps. On the same day, with the same configuration, similar test points were performed at an altitude of 20,000 feet MSL in the relatively uninhabited areas of the Edwards AFB controlled airspace. The maximum range for data link operation was 3.5 nm (21,000 feet) for 1 Mbps and 0.7 nm (4,200 feet) for 11 Mbps. This shows an order-of-magnitude difference between achieved data link range in high and low noise environments, substantiating the expectation that noise level would have a large effect on data link performance. Failure to predict and plan for expected maximum noise levels may result in inadequate link performance in high-noise environments. **Investigate and plan for expected maximum noise levels in the design frequency band for future data links. (R6)**

Air-to-Air Data Link Performance Characteristics

The performance characteristics were assessed quantitatively and qualitatively. Data link performance statistics were collected during all the test points directed at determining the air-to-air data link reception envelope. Additionally, specific test points were flown to gather data on performance related tasks. The results of this testing revealed the efficiency and utility of the data link.

Procedures

The laptops on the host and control aircraft were both configured to collect performance statistics using the Windows® XP Performance Monitor software. The parameters collected were from the network interface statistics: output queue length; packets outbound discarded, packets outbound errors, and packets received errors. These primary statistics describe how efficiently the data link was performing during data transfer operations, using transmission control protocol (TCP) or unit datagram protocol (UDP). Errors and discarded packets demonstrate reduced efficiency and the output queue length will increase as error rates build. The difference between the two protocols is application based – TCP is used when errors in raw data after packaged and received is not tolerable, and UDP is used when errors in the raw data after packaged and received is tolerable. TCP statistics were collected during still image, text file, and pre-recorded video file transfers. UDP statistics were collected during webcam operations – live, streaming video transfers. UDP reduces the data packaging requirements of outbound data because of the presence of human interpretation in the application. The human factor allows for interpretation that is not present in strict data transmissions. For instance the human ear can understand a mispronounced word based on the context the word was used in. The same can be said about video quality. The human eye can look past missing pixels and still glean the overall intended picture.

Another quantitative measure of performance was the time required to transfer operationally representative file types. Actual time measurements were taken during a still image, text file, and pre-recorded video file transfer within the applicable region (high data rate or low data rate) of the data link reception envelope.

The qualitative performance of the data link was assessed using three live data transfers. Live video was streamed using webcams. Text chat was performed throughout the testing using Microsoft® NetMeeting. GPS position of each aircraft was transmitted over the network to the other aircraft and displayed in real-time on FalconView®.

Data Link Performance Results

Overall, the network interface statistics reflected high network efficiency for all data rates and ranges. The output queue length, packet outbound errors, discarded packets received, packet errors received, UDP errors, and transmission control protocol (TCP) errors consistently remained at zero, demonstrating an efficient use of the available data rate during all transmissions. All qualitative tasks were performed effectively (free of software resets) at all data rates and ranges where the network existed. The statistics of performance file transfers made in the 1 Mbps and 11 Mbps reception ranges are listed in table 3.

Table 3. Performance Testing - Time to Transfer

File Type	File Size (kB)	Selected Data Rate (Mbps)	Range (nm)	Time to Transfer (sec)
Text File	2.1	1	5.2	3
Still Image	120	1	5.2	33
Small Video	1280	1	5.2	85
Large Video	18000	11	2.3	32

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CONCLUSIONS AND RECOMMENDATIONS

The Have HALO II test team performed seven formation test flights encompassing 35 flight hours during March 2007 to determine the reception envelope and the performance of an airborne 802.11b Wireless Fidelity (WiFi) data link as a function of range, elevation, azimuth, data rate, amplification level, link configuration, and noise level. The data link envelope was defined in terms of azimuth angle, elevation angle, and slant range. The performance of the data link was defined in terms of data rate, transmission control protocol (TCP) and unit datagram protocol (UDP) error statistics, and network health statistics. All test objectives were met. The conclusions and recommendations are discussed below in priority order.

Flight tested maximum range of the data link closely matched predicted maximum ranges. The 95 percent confidence interval for range with 11 megabits per second (Mbps) and 5 Watts (W) of amplification (1.58 W effective isotropic radiated power) selected was 3.0 to 4.7 nautical miles with a maximum actual data rate of 4.4 Mbps. The 95 percent confidence interval for range with 1 Mbps and 5 W (0.32 W effective isotropic radiated power) selected was 6.2 to 11.3 nm with a maximum actual data rate of 0.7 Mbps.

Performance characteristics of the data link were measured while sending text files, chat data, still images, pre-recorded video, and streaming webcam video between the two aircraft. Network health statistics were gathered for both TCP and UDP activities. Overall, the network health statistics reflected high network efficiency for all data rates and ranges.

Testing was performed on a WiFi network configured in three different ways: Ad Hoc, Infrastructure, and Bridge. The Ad Hoc configuration was found to be the most reliable and capable. Hardware errors associated with the SecNet11® WiFi cards were encountered in the Infrastructure and Bridge modes which were frequent, persistent, and highly disruptive to the test. **Investigate why SecNet11® demo cards experienced frequent failures during flight test in Bridge and Infrastructure configurations. (R1)**

Two different power amplification levels were tested, 1 Watt (W) and 5 W (the power output of the amplifier), which yielded 0.32 W and 1.58 W effective isotropic radiated power. Excessive cable and connector losses caused severe attenuation of the signal, which reduced the data link ranges achieved during testing. The antenna patterns were found to be relatively uniform throughout the hemisphere (top or bottom) covered by each antenna. **Use low-loss cabling for the appropriate frequency and mount the amplifiers as near the antenna as possible to maximize data link range. (R5)**

The effect of background noise level on data link performance was investigated by comparing maximum data link range in high and low noise levels. As expected, the maximum data link range in the high noise environment was an order-of-magnitude less than that obtained in the low noise environment. An unexpected effect was the variation in noise level and corresponding data link maximum range in the low noise environment. **Investigate and plan for expected maximum noise levels in the design frequency band for future data links. (R6)**

The data rate selected was found to have an impact on the reception range achieved. There were small differences between the range results of the automatic (AUTO) and 11 Mbps selected data rates. However, 1 Mbps yielded twice the reception range of AUTO. **For maximum range, select the 1 Mbps data rate. (R2)**

Flight test techniques were designed to capture azimuth and elevation dependencies of the reception ranges. Design of experiments analysis did not reflect any azimuth or elevation dependencies present in the data retrieved from test points flown with 1 W or 5 W amplifications. Although tail-to-tail test points appeared to regularly yield reduced reception ranges, there were not enough replicates of the test points to gain statistical significance of the azimuth dependence. **Fly additional varying range and varying elevation test points to refine the azimuth and elevation dependence of the data link reception envelope. (R4)**

The actual data rates did not match the selected data rates available to each physical configuration. The selections available were: AUTO, 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps. The observed data rates were much lower than the selected data rates. Knowing the over-the-air data rate gives the user baseline information for developing potential applications for use across the data link. **Publish the actual data rates as a function of the physical configuration and data rate selection for application considerations. (R3)**

REFERENCES

1. IEEE 802.11 Wireless LANS Standard, http://standards.ieee.org/getieee802/802.11.html

2. Limited Evaluation of an 802.11b Air-to-ground Wireless Datalink, Project “Have HALO” Technical Report, AFFTC-TIM-06-03, USAF Test Pilot School, Edwards AFB, June 2006.

3. *Haigh-Farr Blade Antenna Data Sheet*, Haigh-Farr Inc., Bedford, NH, 31 Jan 2007. http://www.haigh-farr.com/datasheets/blade.pdf

4. 2.4 GHz High Power WiFI Amplifiers with Switchable Power Control, Hyperlink Technologies, 7 Jun 2007. http://www.hyperlinktech.com/web/24ghz_switchable_high_power_wifi_amplifiers.php

5. SecNet11® Plus Secure Wireless LAN PC Card, Harris Corp., Melbourne, FL, 7 Feb 2007. http://www.govcomm.harris.com/secure-comm/products/pc-card.html

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APPENDIX A – DETAILED TEST ARTICLE DESCRIPTION

The system under test (SUT) on each C-12C aircraft consisted of a Haigh-Farr® aerial blade omnidirectional antenna mounted on the top and bottom of the aircraft (Ref 3). The bottom antenna was located between the main landing gear as shown in figure A-1. The top antenna was located just aft of the front cockpit as shown in figure A-2. Each antenna was connected to a 1 or 5 Watt selectable Hyperlink Technologies® (Ref 4) amplifier located on the top of the DAS rack in the C-12C cabin by RG-400 cabling, figure A-3. The amplifier was connected directly to Harris Corporation's SecNet11® demonstration wireless network card (Ref 5) through RG-316 cabling and the wireless card was then inserted into the access point or laptop computer depending on the configuration being tested. Dell Latitude® laptop PCs with Windows® XP, NetStumbler® software, Windows® XP Performance Monitor software, and a web-based camera for real-time video transfer using Microsoft® NetMeeting® completed the SUT configuration being tested.

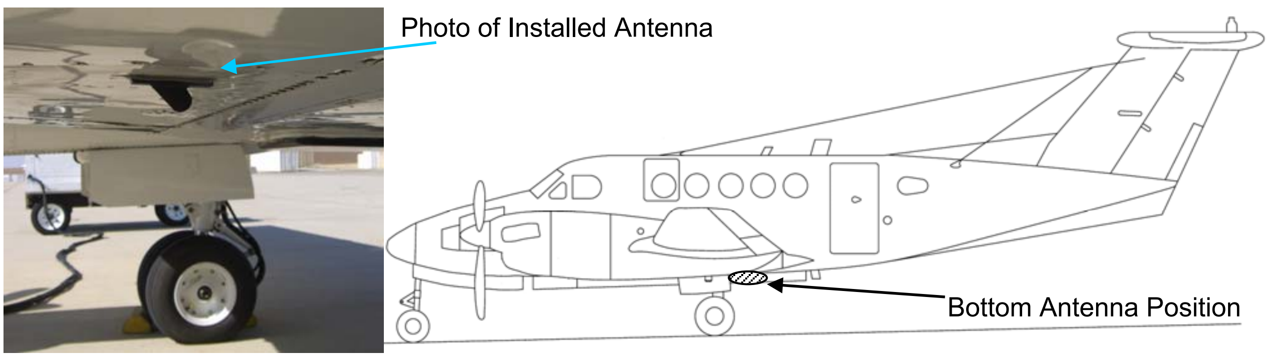

Figure A-1. Haigh-Farr® Antenna Position on Bottom of C-12C Test Aircraft

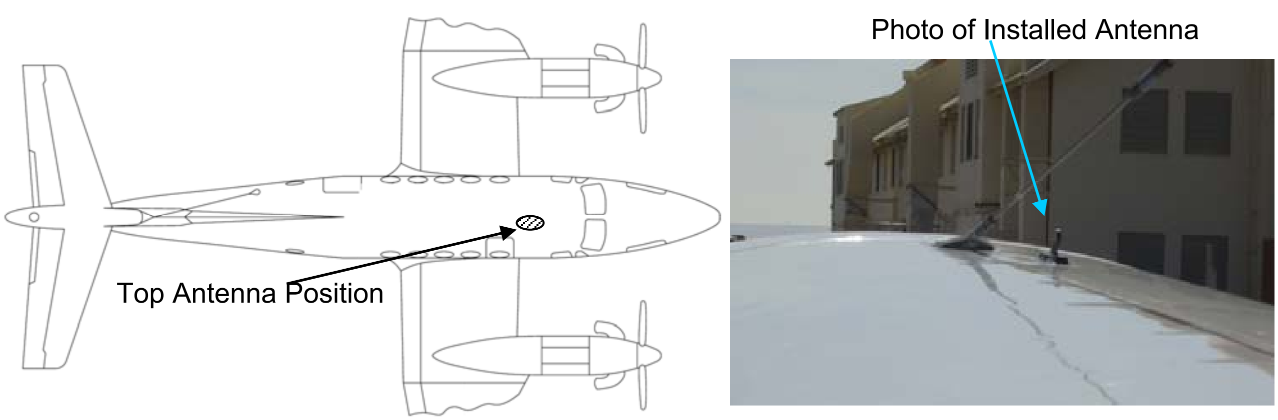

Figure A-2. Haigh-Farr® Antenna Position on Top of C-12C Test Aircraft

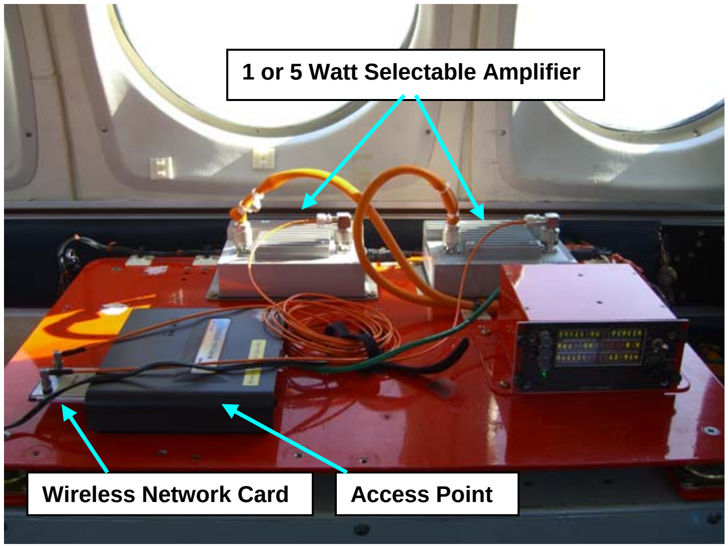

Figure A-3. Test Equipment Mounted to the Data Acquisition System Rack

NetStumbler® is a software tool used by Microsoft® Windows® to detect WiFi networks using the 802.11a, 802.11b, and 802.11g WiFi standards. NetStumber® was used to verify the network configuration and to collect signal-to-noise ratio (SNR) data throughout the test. Windows® XP Performance Monitor software allowed the test team to monitor real time data transmission across the WiFi link and to collect detailed send and receive data packet information from the data transmissions. Microsoft® NetMeeting® was the software tool used to conduct real time video transfers between the two test aircraft using the attached web-cameras. Real time text chat sessions were also accomplished between the aircraft using Microsoft® NetMeeting®. A GARMIN® GPS receiver was connected to a GPS antenna mounted on the tail of the C-12C aircraft. The GPS receiver data was used for data link synchronization and to provide aircraft location coordinates directly into the Windows® XP Performance Monitor software and FalconView® software. Additionally, an Itronix Duo-Touch® tablet PC was used in each aircraft to monitor the wireless data link network performance and ambient noise in the WiFi spectrum. The airborne data link was transmitted with either 1 or 5 Watts of amplification over the omnidirectional antennas at a frequency of 2.4 GHz to 2.5 GHz. Table A-1 provides a detailed list of the hardware and software components used during testing.

Table A-1. Components of the Have HALO II System Under Test

Component	**Model**	**Manufacturer**
Aerial Blade Antennas	6030-2	Haigh-Farr®
Selectable 1 or 5 Watt Amplifiers	HA240105GAI-NF	Hyperlink Technologies®
GPS Receiver	GPSMAP 296	Garmin®
Laptop	Latitude D620	Dell®
Wireless Network Card	SecNet11® Demo Card	Harris Corporation
Duo Touch Tablet PC	IX325	Itronix®
Web-Cameras (x2)	Quickcam®	Logitech®
NetStumber®	Version 0.4.0	Netstumbler.com
Windows® XP Performance Monitor	Version 5.1	Microsoft®
NetMeeting®	Version 3.01	Microsoft®

During testing three physical configurations of the air-to-air data link were used: Infrastructure, Bridge, and Ad Hoc. The Infrastructure configuration consisted of one test aircraft using the configuration shown in figure A-4, access point configuration, and the other test aircraft using the configuration shown in figure A-5, card in the laptop configuration. The Bridge configuration consisted of both test aircraft using the configuration shown in figure A-4, access point configuration. The Ad Hoc configuration consisted of both test aircraft using the configuration shown in figure A-5, card in laptop configuration.

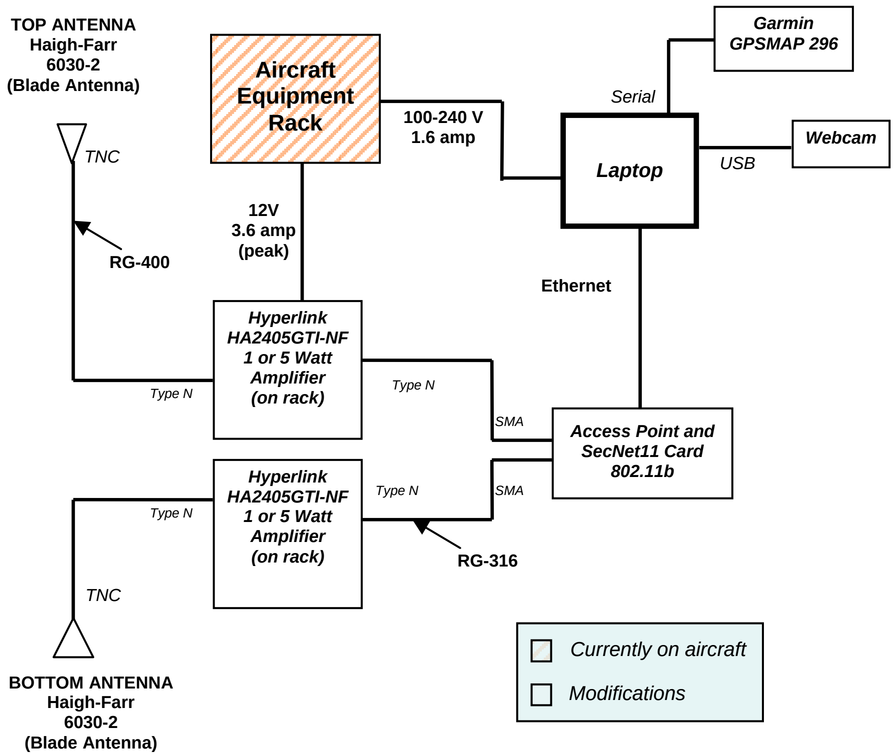

Figure A-4. Configuration with SecNet11® Card in Access Point

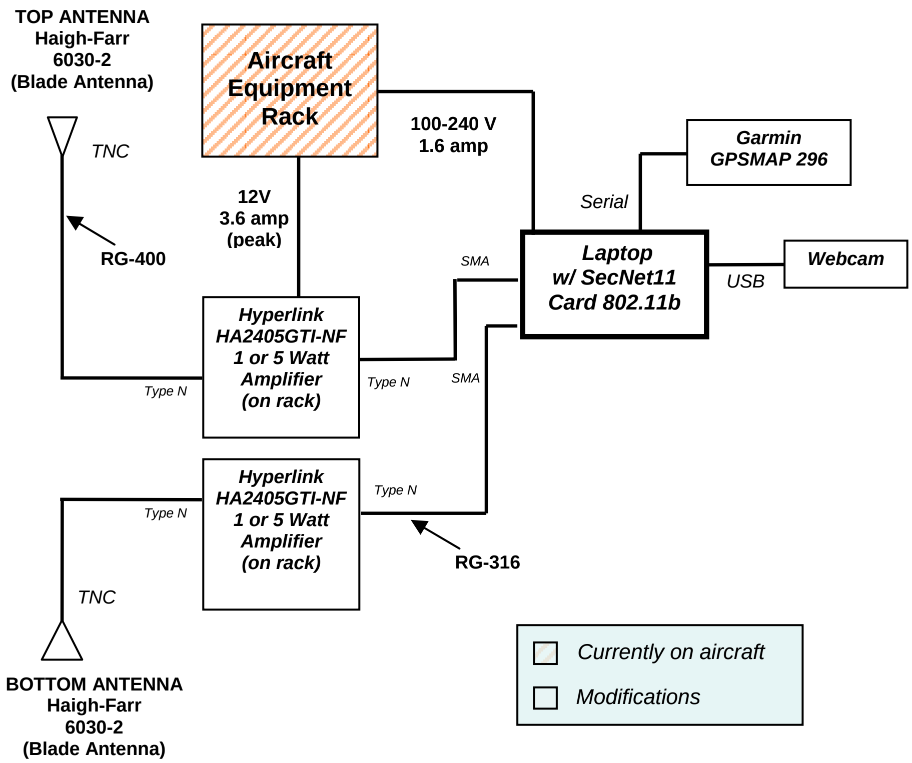

Figure A-5. Configuration with SecNet11® Card in Laptop

APPENDIX B – PREDICTED MAX RANGE CALCULATIONS

The predicted maximum range of the data link was determined using the one-way link setup shown in figure B-1. The *host* aircraft transmitted data to the *control* aircraft using the estimated parameters below. This link architecture applies to all of the modes tested, including Infrastructure, Bridge, and Ad Hoc. In this setup, the SecNet11® card transmitted data from its two ports via a RG-316 cable to each amplifier. Cable and connector losses were estimated to be 4 dB from the SecNet11® card to the amplifier. Since the SecNet11® card was selected to operate in the "Antenna Diversity" mode, the card would determine the antenna based upon the greater receive SNR. The RF amplifier then amplified the signal to either 5 Watts (37 dBm) or 1 Watt (30 dBm) as selected in flight. RG-400 cable was used to connect the amplifier to the antenna, accounting for approximately 8 dB cable and connector loss at 2.4 GHz. The Haigh-Farr blade antenna gain was estimated as 3 dBi with assumed to be omnidirectional with a filled-in null for purposes of calculating the maximum range. Free space and atmospheric losses across the data link were modeled to determine the maximum range of the datalink. On the host aircraft, the signal was received by an identical model of the Haigh-Farr blade antenna, assumed to be a constant 3 dBi gain. Identical cable and connector losses were estimated between the antenna and amplifier, and the amplifier and the SecNet11® card. The amplifier delivered 17 dB of gain to the received signal strength, per specifications provided by the manufacturer. The receive sensitivities were estimated for the 11 Mbps and 1 Mbps selected data rate modes as -78.5 dBm and -85.5 dBm, respectively.

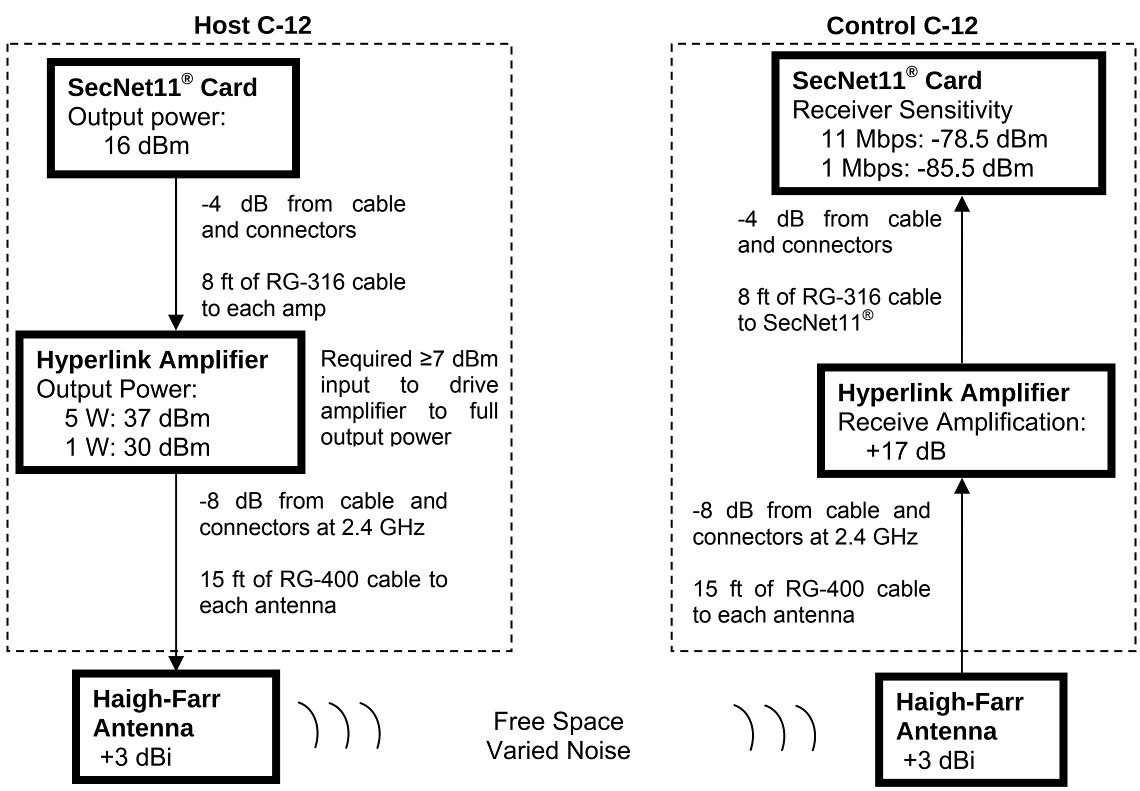

Figure B-1. One-way RF Link Gains/Losses

The gains and losses from the one-way RF link were used to predict the maximum range of the data link for four different configurations, including 1 or 5 Watt amplifiers and 1 or 11 Mbps selected data rate. The predicted maximum ranges are found in table B-1.

Table B-1. Predicted Data Link Reception Ranges

Configuration	Amp	dBm	Frequency (GHz)	Host Cable/ Conn Loss	Ant Gain	Rcv Gain	Control Cable/ Conn Loss	Link Sensitivity (dBm)	Free Space Loss	Predicted Range (nm)
1 W, 11 Mbps	1 W	+30	2.400	-8	+6	+17	-12	-78.5	-111.5	**2.0**
1 W, 1 Mbps	1 W	+30	2.400	-8	+6	+17	-12	-85.5	-118.5	**4.5**
5 W, 11 Mbps	5 W	+37	2.400	-8	+6	+17	-12	-78.5	-118.5	**4.5**
5 W, 1 Mbps	5 W	+37	2.400	-8	+6	+17	-12	-85.5	-125.5	**10.1**

APPENDIX C – FLIGHT TEST MANEUVER DESCRIPTIONS

Varying Range FTT

The varying range FTT was used to measure the effect of varying range for a constant azimuth and elevation. The two test aircraft started in line abreast formation at the same altitude. At the beginning of the test point, the aircraft turned away from each other an equal and specified number of degrees and tracked away from each other at a fixed heading until data link break. After data link broke, both test aircraft simultaneously turned back to the reciprocal heading with the lead aircraft identifying which aircraft was at the higher altitude and track inbound. While range was closing, data were collected on link establishment and characteristics. The 1,000 foot altitude separation was maintained until visual contact was acquired, then the aircraft returned to being at the same altitude. The test point was terminated when range was visually estimated to be 3,000 foot. After the test point was terminated, the aircraft maneuvered as required to rejoin to line abreast formation in preparation for the next test point.

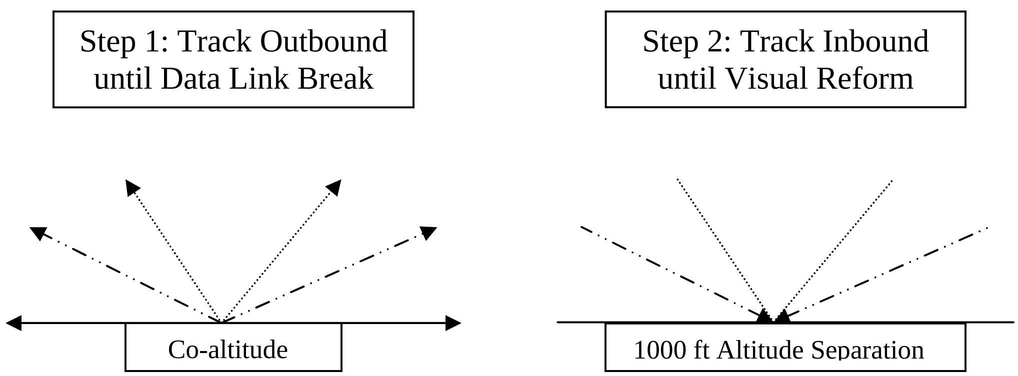

Figure C-1. Varying Range FTT

Varying Elevation FTT

The varying elevation FTT was used to measure the effect of varying elevation and range for a constant azimuth. Test aircraft started in line abreast formation with a 5,000 foot altitude stack. They then performed the varying range FTT with the added altitude difference. This resulted in a continuous variation of elevation and range.

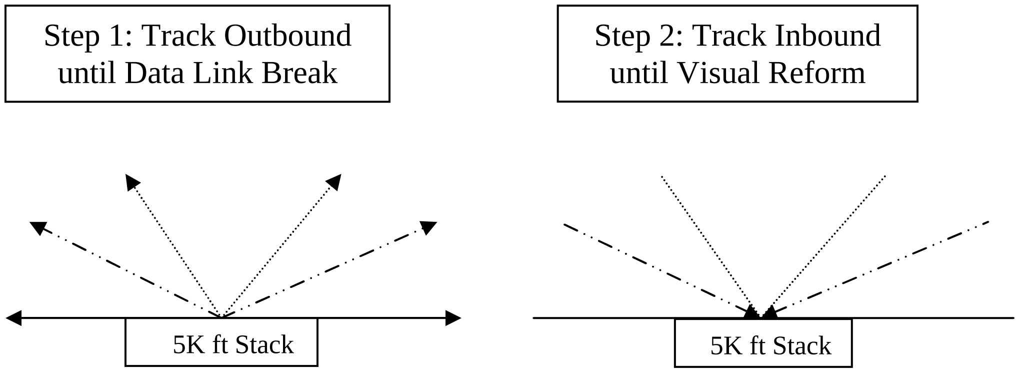

Figure C-2. Varying Elevation FTT

Constant Relative Position FTT

The constant relative position FTT was used to get high-fidelity data at fixed azimuth, elevation, and range. The aircraft flew at specified range, altitude differential, and azimuth. While any azimuth was tested with this FTT, it normally was planned for a line abreast (90 degree azimuth) formation.

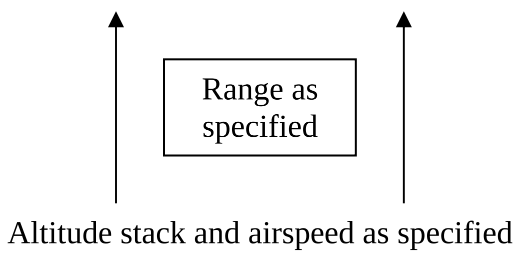

Figure C-3. Constant Relative Position FTT

Maneuvering Flight FTT

The maneuvering flight FTT was used to capture dynamic effects on the data link performance. The test aircraft set position and characterized data link quality using the Constant Relative Position FTT. After this setup, both aircraft began continuous turns using a 45 degree bank angle. This resulted in continually changing azimuth and elevation (in the aircraft body axis).

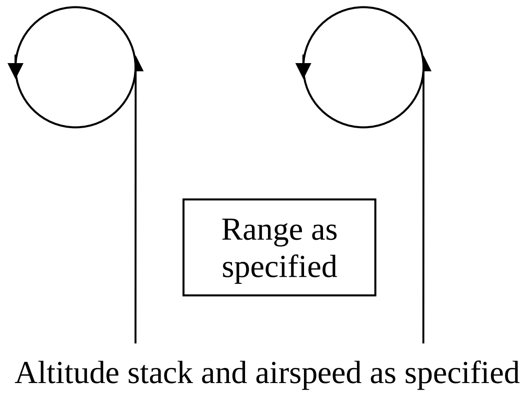

Figure C-4. Maneuvering Flight FTT

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APPENDIX D – TEST CONDITION MATRIX

Test points were flown to define the envelope of the data link on all flights. The test matrix included test points in the Infrastructure, Bridge, and Ad Hoc configurations, as shown in tables D-1, D-2, and D-3. Test points were flown in the high noise environment on flights 6-7 and are listed in table D-4.

Table D-1. Infrastructure Mode Test Matrix

Flight	Flight Test Technique	Range (nm)	Angle off Tail (degrees)	SNR/ Data Rate (Mbps)	Amplifier Power (Watts)
1	Constant Relative Position	1	90	SNR	5
1	Constant Relative Position	2	90	SNR	5
1	Constant Relative Position	3	90	SNR	5
1	Varying Range 90	Varied	0	SNR	5
1	Varying Range 90	Varied	180	SNR	5
1	Varying Range 60	Varied	30	SNR	5
1	Varying Range 60	Varied	150	SNR	5
1	Varying Range 30	Varied	60	SNR	5
1	Varying Range 30	Varied	120	SNR	5
1	Varying Range 90	Varied	0	AUTO	5
1	Varying Range 90	Varied	180	AUTO	5
1	Varying Range 60	Varied	30	AUTO	5
1	Varying Range 60	Varied	150	AUTO	5
1	Varying Range 30	Varied	60	AUTO	5
1	Varying Range 30	Varied	120	AUTO	5

Table D-2. Bridge Mode Test Matrix

Flight	Flight Test Technique	Range (nm)	Angle off Tail (degrees)	Data Rate (Mbps)	Amplifier Power (Watts)
2	Constant Relative Position	3	90	11	5
2	Constant Relative Position	4	90	11	5
2	Constant Relative Position	5	90	11	5
2	Varying Range 90	Varied	0	11	5
2	Varying Range 90	Varied	180	11	5
2	Varying Range 60	Varied	30	11	5
2	Varying Range 60	Varied	150	11	5
2	Varying Range 30	Varied	60	11	5
2	Varying Range 30	Varied	120	11	5
2	Varying Elevation 90	Varied	0	11	5
2	Varying Elevation 90	Varied	180	11	5
2	Varying Elevation 60	Varied	30	11	5
2	Varying Elevation 60	Varied	150	11	5
2	Varying Elevation 30	Varied	60	11	5
2	Varying Elevation 30	Varied	120	11	5

Table D-3. Ad Hoc Mode Test Matrix

Flight	Flight Test Technique	Range (nm)	Angle off Tail (degrees)	Data Rate (Mbps)	Amplifier Power (Watts)
3	Constant Relative Position	2.5	90	AUTO	5
3	Constant Relative Position	3.4	90	AUTO	5
3	Constant Relative Position	4.2	90	AUTO	5
3	Varying Range 90	Varied	0	AUTO	5
3	Varying Range 90	Varied	180	AUTO	5
3	Varying Range 60	Varied	30	AUTO	5
3	Varying Range 60	Varied	150	AUTO	5
3	Varying Range 60	Varied	30	11	5
3	Varying Range 60	Varied	150	11	5
3	Varying Range 60	Varied	30	1	5
3	Varying Range 60	Varied	150	1	5
3	Varying Range 30	Varied	60	AUTO	5
3	Varying Range 30	Varied	120	AUTO	5
3	Varying Elevation 90	Varied	0	AUTO	5
3	Varying Elevation 90	Varied	180	AUTO	5
3	Varying Elevation 60	Varied	30	AUTO	5
3	Varying Elevation 60	Varied	150	AUTO	5

Table D-3. Ad Hoc Mode Test Matrix (cont)

Flight	Flight Test Technique	Range (nm)	Angle off Tail (degrees)	Data Rate (Mbps)	Amplifier Power (Watts)
3	Varying Elevation 30	Varied	60	AUTO	5
3	Varying Elevation 30	Varied	120	AUTO	5
4	Constant Relative Position	6	90	1	5
4	Constant Relative Position	8	90	1	5
4	Constant Relative Position	10	90	1	5
4	Constant Relative Position	12	90	1	5
4	Constant Relative Position	5	90	2	5
4	Constant Relative Position	5	90	5.5	5
4	Varying Range 90	Varied	0	1	5
4	Varying Range 90	Varied	180	1	5
4	Varying Range 60	Varied	30	1	5
4	Varying Range 60	Varied	150	1	5
4	Varying Range 60	Varied	30	2	5
4	Varying Range 60	Varied	150	2	5
4	Varying Range 60	Varied	30	5.5	5
4	Varying Range 60	Varied	150	5.5	5
4	Varying Range 60	Varied	30	1	1
4	Varying Range 60	Varied	150	1	1
4	Varying Range 30	Varied	60	1	5
4	Varying Range 30	Varied	120	1	5
5	Constant Relative Position	1	90	1	1
5	Constant Relative Position	2	90	1	1
5	Constant Relative Position	2	90	1	5
5	Constant Relative Position	4	90	1	5
5	Constant Relative Position	4	90	1	5
5	Maneuvering Flight	1	Varied	1	5
5	Maneuvering Flight	2	Varied	1	5
5	Maneuvering Flight	1	Varied	1	1
5	Varying Range 60	Varied	30	1	5
5	Varying Range 60	Varied	150	1	5
5	Varying Range 60	Varied	30	2	5
5	Varying Range 60	Varied	150	2	5
5	Varying Range 60	Varied	30	5.5	5
5	Varying Range 60	Varied	150	5.5	5
5	Varying Range 60	Varied	30	11	5
5	Varying Range 60	Varied	150	11	5
6	Constant Relative Position	3.5	90	1	1
6	Constant Relative Position	1	90	11	1
6	Constant Relative Position	1.5	90	11	1

Table D-3. Ad Hoc Mode Test Matrix (cont.)

Flight	Flight Test Technique	Range (nm)	Angle off Tail (degrees)	Data Rate (Mbps)	Amplifier Power (Watts)
6	Constant Relative Position	1.5	90	11	5
6	Constant Relative Position	2	90	11	5
6	Constant Relative Position	3	90	11	5
6	Varying Range 90	Varied	0	1	1
6	Varying Range 90	Varied	180	1	1
6	Varying Range 90	Varied	0	11	1
6	Varying Range 90	Varied	180	11	1
6	Varying Range 90	Varied	0	11	5
6	Varying Range 90	Varied	180	11	5
6	Varying Range 60	Varied	30	11	1
6	Varying Range 60	Varied	150	11	1
6	Varying Range 30	Varied	60	1	1
6	Varying Range 30	Varied	120	1	1
6	Varying Range 30	Varied	60	11	1
6	Varying Range 30	Varied	120	11	1
6	Varying Range 30	Varied	60	11	5
6	Varying Range 30	Varied	120	11	5
7	Maneuvering Flight	3.2	Varied	1	1
7	Maneuvering Flight	1.2	Varied	11	1
7	Maneuvering Flight	2.8	Varied	11	5
7	Varying Elevation 90	Varied	0	1	1
7	Varying Elevation 90	Varied	180	1	1
7	Varying Elevation 90	Varied	0	1	5
7	Varying Elevation 90	Varied	180	1	5
7	Varying Elevation 90	Varied	0	11	5
7	Varying Elevation 90	Varied	180	11	5
7	Varying Elevation 60	Varied	30	1	1
7	Varying Elevation 60	Varied	150	1	1
7	Varying Elevation 60	Varied	30	1	5
7	Varying Elevation 60	Varied	150	1	5
7	Varying Elevation 60	Varied	30	11	5
7	Varying Elevation 60	Varied	150	11	5
7	Varying Elevation 30	Varied	60	1	1
7	Varying Elevation 30	Varied	120	1	1
7	Varying Elevation 30	Varied	60	1	5
7	Varying Elevation 30	Varied	120	1	5
7	Varying Elevation 30	Varied	60	11	5
7	Varying Elevation 30	Varied	120	11	5

Table D-4. Ad Hoc Mode Test Matrix (High Noise Environment)

Flight	Flight Test Technique	Range (nm)	Angle off Tail (degrees)	SNR/ Data Rate (Mbps)	Amplifier Power (Watts)
6	Palmdale/Lancaster Run	Varied	90	1	1
6	Palmdale/Lancaster Run	Varied	90	1	1
6	Palmdale/Lancaster Run	Varied	90	11	1
6	Palmdale/Lancaster Run	Varied	90	11	1
7	Palmdale/Lancaster Run	Varied	90	SNR	1
7	Palmdale/Lancaster Run	Varied	90	SNR	1
7	Palmdale/Lancaster Run	Varied	90	SNR	1
7	Palmdale/Lancaster Run	Varied	90	SNR	1

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APPENDIX E – PLOTS OF RESULTS

The reception envelope of the data link was defined using the flight test techniques described in appendix C. For each maneuver, a plot similar to figure E-1 was derived. Figure E-1 shows an example of the data collected during a Varying Range maneuver with a 30 degree turn off the reference heading. The plot shows the breakdown of the data rates relative to the host aircraft, as well as the total data rate between both aircraft. Some key range values were taken from these maneuvers, to include the range where the full data rate dropped below 90 percent of its value for at least five seconds. This value is referred to as the *full data rate range*. The other key value taken from the maneuver is the *link break range* which is the range where the data link did not transfer any data for at least five seconds. These range values were collected for all maneuvers to define the reception envelope and the results of the shown in figures E-2 through E-8. Due to the large number of plots developed from the reception envelope determination, all of the plots showing the data rate and SNR values are not include shown in this report. The plots are included in a data CD submitted with this report.

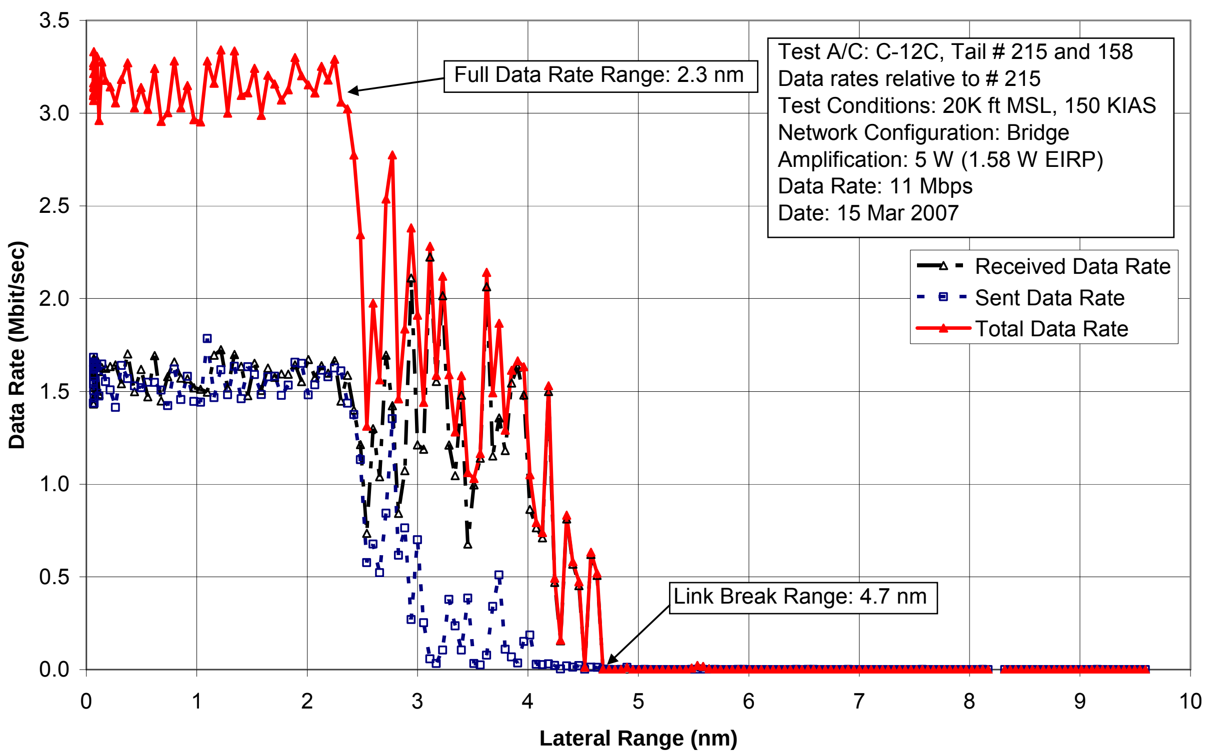

Figure E-1. Example data rate collected during Varying Range FTT (30 deg Outbound)

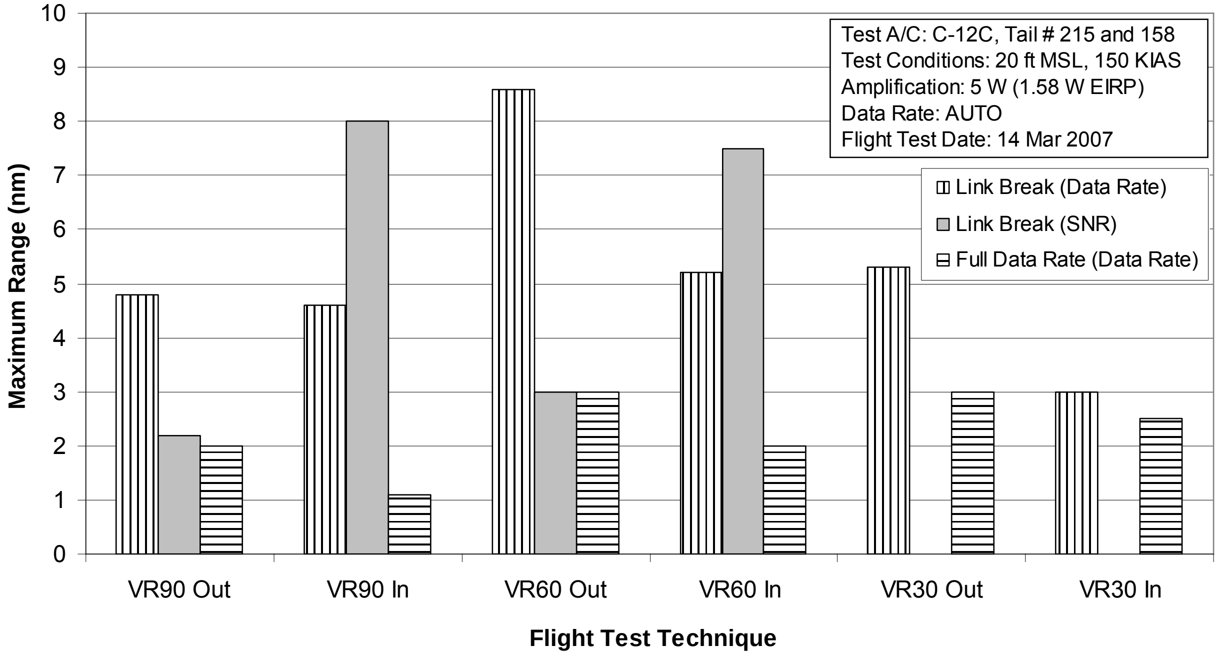

Figure E-2. Infrastructure Mode, Auto Data Rate, 5W Amplification

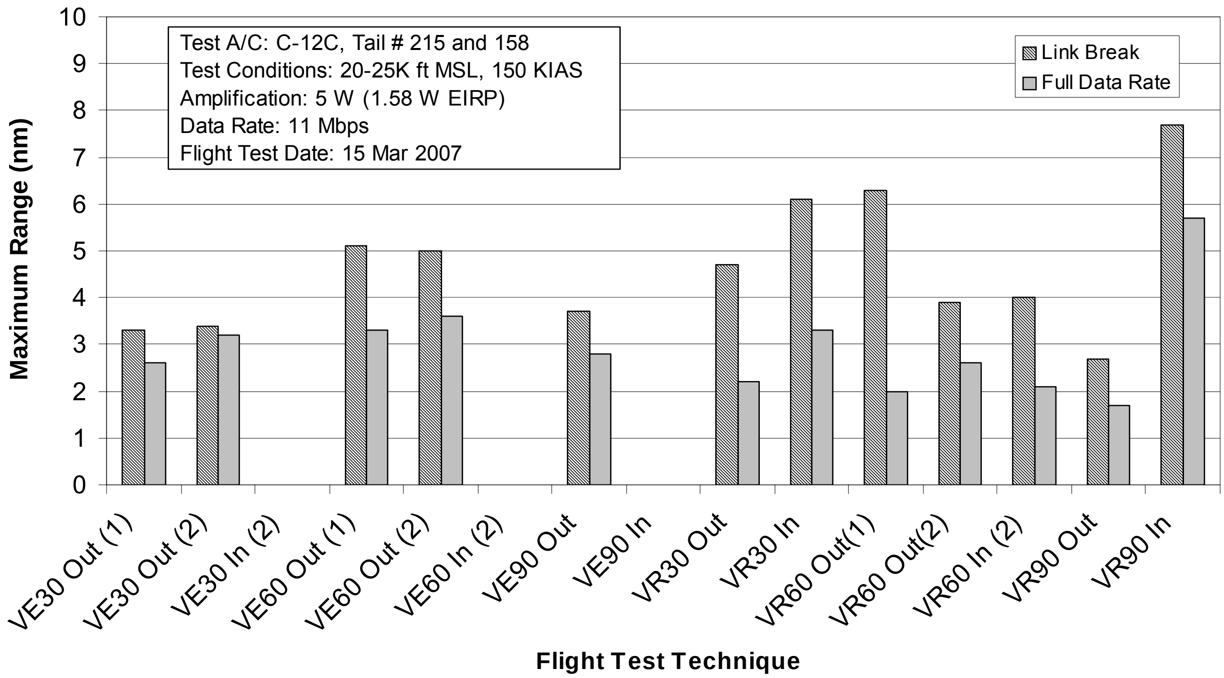

Figure E-3. Bridge Mode, 11 Mbps Data Rate, 5 W Amplification

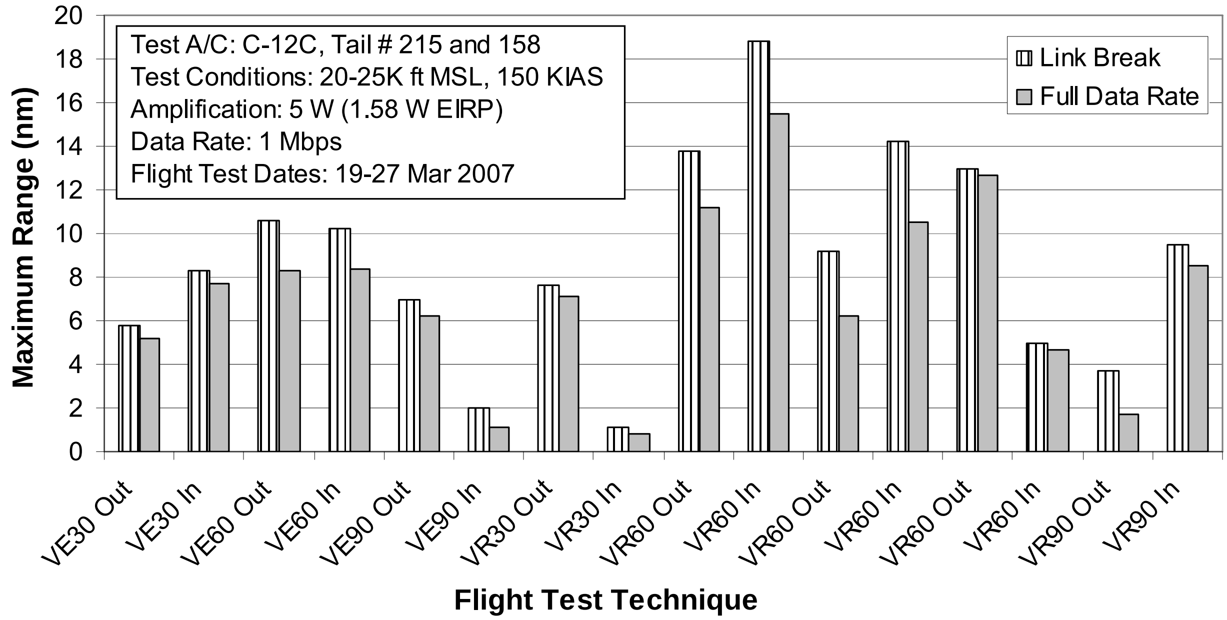

Figure E-4. Ad Hoc Mode, 1 Mbps Data Rate, 5 W Amplification

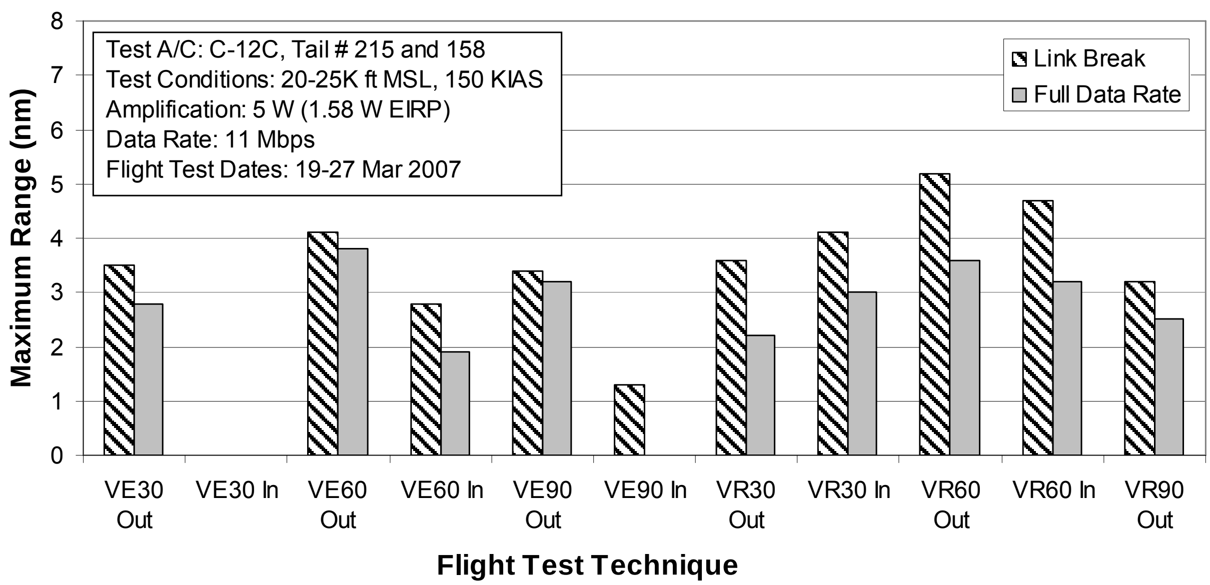

Figure E-5. Ad Hoc Mode, 11 Mbps Data Rate, 5 W Amplification

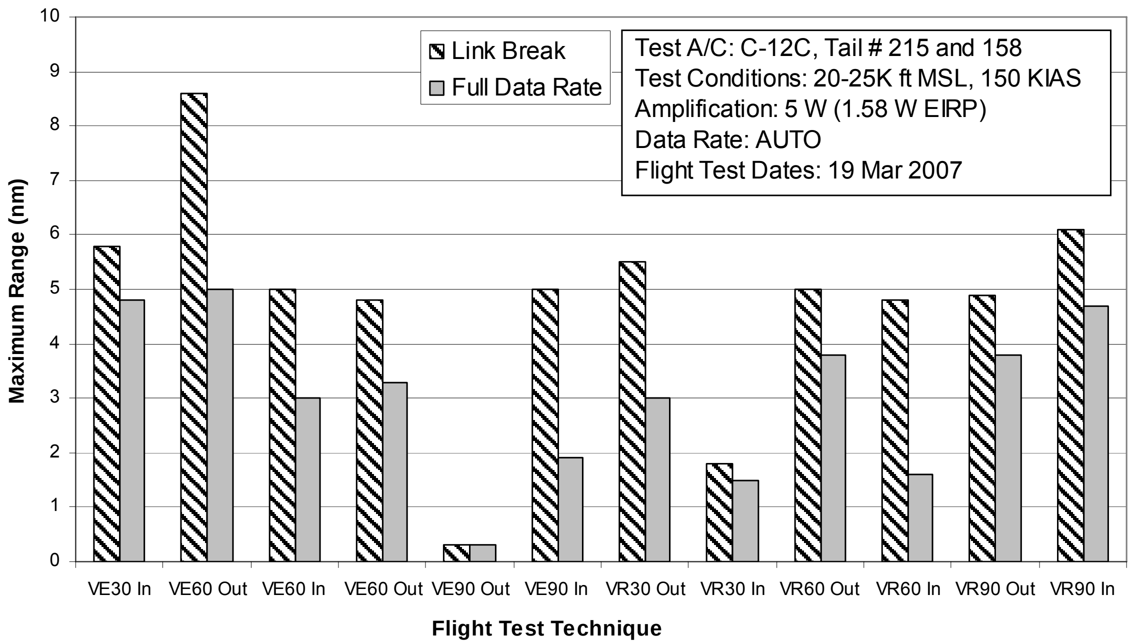

Figure E-6. Ad Hoc Mode, Auto Data Rate, 5W Amplification

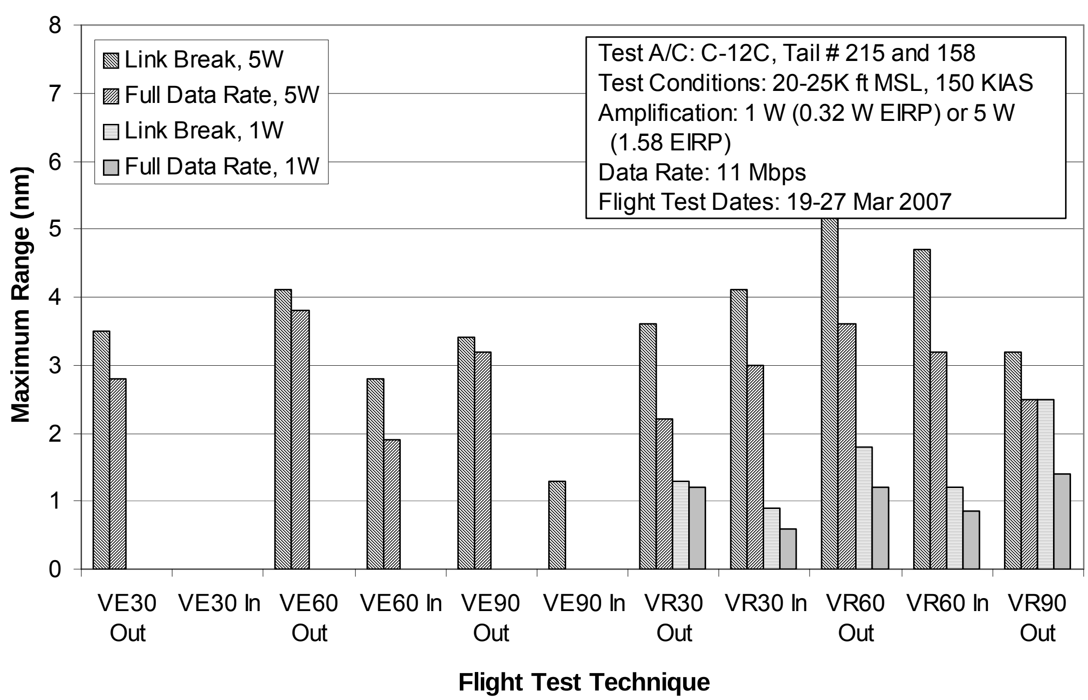

Figure E-7. Ad Hoc Mode, 11 Mbps Data Rate, Varying Amplification

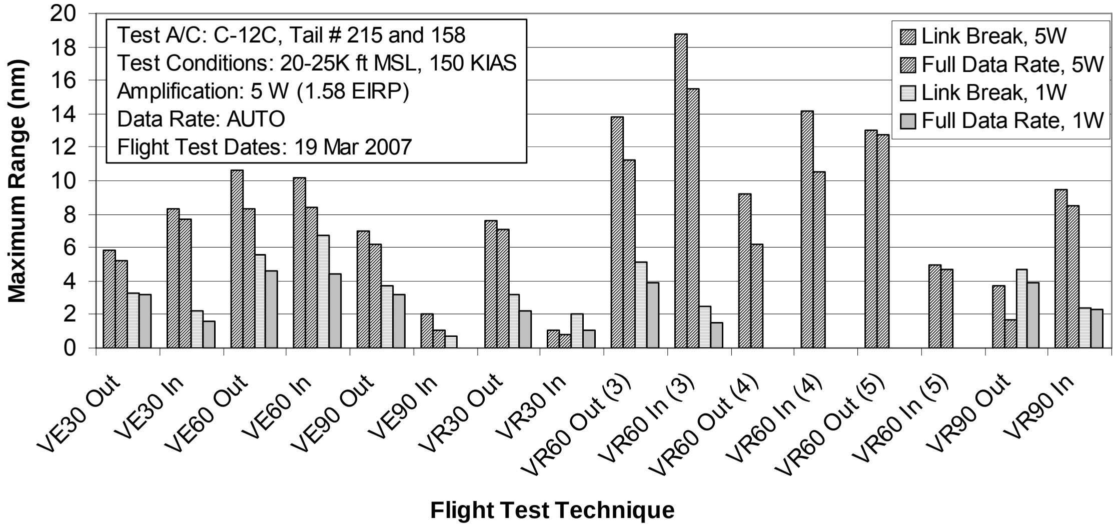

Figure E-8. Ad Hoc Mode, 1 Mbps Data Rate, Varying Amplification

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APPENDIX F – LIST OF ACRONYMS

ACC	Air Combat Command
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AGL	above ground level
amp	amperes
CD	compact disk
CI	confidence interval
CMMU	cache memory monitor unit
DAS	data acquisition system
DOE	design of experiments
dB	decibels
dBi	decibels relative to isotropic radiating pattern
dBm	decibels of power relative to 0.001 Watt
FCC	Federal Communications Commission
ft	foot/feet
FTE	flight test engineer
FTT	flight test technique
GHz	gigahertz
GPS	global positioning system
HALO	Huron Airborne Link Optimization
kB	kilobytes
KIAS	knots indicated airspeed
KTAS	knots true airspeed
Mbps	megabits per second
MB	megabytes
MHz	megahertz
MSL	mean sea level
N/A	not applicable
nm	nautical miles

PAR	program assessment review
PC	personal computer
PID	program information document
RF	radio frequency
SNR	signal-to-noise ratio
SUT	system under test
TCP	transmission control protocol
TIM	technical information memorandum
TMP	Test Management Project
TPS	Test Pilot School
TPS/CS	Test Pilot School Education Division, Curriculum Support
TPS/EDT	Test Pilot School Education Division, Test Management Branch
TW	Test Wing
UDP	user datagram protocol
USAF	United States Air Force
USAFTPS	United States Air Force Test Pilot School
USB	universal serial bus
V	volts
VMC	visual meteorological conditions
VE30	varying elevation FTT with 30 degrees turn off reference heading
VE60	varying elevation FTT with 60 degrees turn off reference heading
VE90	varying elevation FTT with 90 degrees turn off reference heading
VR30	varying range FTT with 30 degrees turn off reference heading
VR60	varying range FTT with 60 degrees turn off reference heading
VE90	varying range FTT with 90 degrees turn off reference heading
VoIP	Voice Over Internet Protocol
W	Watt
WiFi	wireless fidelity

APPENDIX G – LESSONS LEARNED

- Further testing should be performed using FalconView® to display the position of both aircraft on the laptop on a moving map display.

- Three FTEs were required to adequately test on each sortie. Consider the FTE workload of testing with high performance aircraft with only one FTE in each aircraft.

- On varying elevation FTT, there was a true airspeed difference due to the altitude difference. To fly correct patterns, adjust KCAS according to KTAS.

- The FTEs had no capability to transmit on the radio. This led to the pilot relaying instructions over the radio in many instances. At best, this resulted in delays and increased workload for all crewmembers. At worst, it introduced confusion and mistakes that cost test time.

- Get low-loss cabling for the frequency band of interest. High-loss cabling is not operationally representative and can single-handedly kill the performance of the system.

- Successful formation flight testing hinged on good communication and direction. The test team helped that happen by having the pilot flying/aircraft commander focus on flying the aircraft and the pilot not-flying acting as the formation lead. This division of labor was very successful.

- The impact of not attaining the SNR data was minimal for outbound maneuvers; however, SNR data would have provided a better range value for the inbound maneuvers than the data rate method. This was because inbound maneuvers required the laptop operator of the control aircraft to continue to monitor the signal strength and quality window of the cache memory monitor unit (CMMU) and then begin looking for the host laptop when the operator thought the link was/should be available. This was a persistent problem with getting good range data during inbound maneuvers because of the method required to first "see" the host laptop, and then initiate data transfers. This problem, which stems from the basic network characteristics within the Windows® operating system, heavily influenced the range data for all inbound maneuvers. Indeed, the reported range data for all inbound maneuvers should be considered to be specific to this specific task (file transfer within Windows®). Future applications should be designed to automate the re-establishment of the data link and to automate data transfer after establishment of the data link.

- Read Have HALO I technical report for more lessons learned.

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